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Evidence of muonium formation using thin gold foils in vacuum*

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The production of thermal muonium in a vacuum region has been investigated using an array of 200 thin (~ 1000 Å thick) gold foils exposed to a stopping μ^+ beam. By examining the observed time dependence of the μ^+-decay spectra in various transverse magnetic fields, we estimate that the lower limit of the probability of muonium formation by these gold foils placed in vacuum was 0.28 ± 0.05.

I. INTRODUCTION

It has been recognized that the study of quantum electrodynamics and/or weak interactions using the muonium atom (μ^+e^-) would be enhanced if the muonium atom could be isolated in a vacuum, or free space, environment. For example, the investigation of the muonium-antimuonium ($\mu^+e^- \rightarrow \mu^-e^+$) transition[1,2] in a free-space environment would enable one to test the nature of the lepton-number conservation law.[2,3]

In this paper, we present evidence for the formation of muonium atoms of thermal energy using an array of thin (1000-Å) gold foils placed in a vacuum environment.[4] The presence of muonium in the vacuum region between the foils was demonstrated by the observation of muonium precession signals when the foils were exposed to a stopping μ^+ beam. By comparing the observed μ^+-decay asymmetries with those measured in a low-pressure argon-gas target and in a thin quartz-plate target under the same experimental conditions,[5] we determined the amplitude for muonium formation by the thin gold foils in vacuum.

Gold was chosen as the foil material mainly because proton-charge-exchange data indicate that a large H^0 component emerges from such a foil at low energies.[6] It was found that the H^0 component was 80% at 10 keV, increasing to 90% at the lowest energy studied, namely, 0.65 keV.[7] For a complex atomic system, such as gold, there exists the possibility that the charge-exchange cross section σ_{10} remains substantial at much lower energies than is the case for a light noble gas like argon.[8] In addition, gold is known to be chemically inactive, a condition which may encourage the release of surface contaminants. Our foils were the thinnest gold leaf commercially available, 1000 Å thick and 74 cm^2 in area. The principal arrangement used 200 such foils, each suspended by a thread from a frame of lightweight stainless steel, and separated one from another by 0.08 cm on the average.

Figure 1 provides a top view of the experimental arrangement. A "stretched" beam of backward-produced positive muons emerging from the Space Radiation Effects Laboratory (SREL) synchrocyclotron meson channel was deflected into the counter array. Stopping muons (20 sec^{-1}g^{-1}) were identified by the coincidence 1 2 $\bar{3}$ 4 5 $\bar{6}$; the subsequent decay positrons by the signal (2) (3) (4) in anticoin-

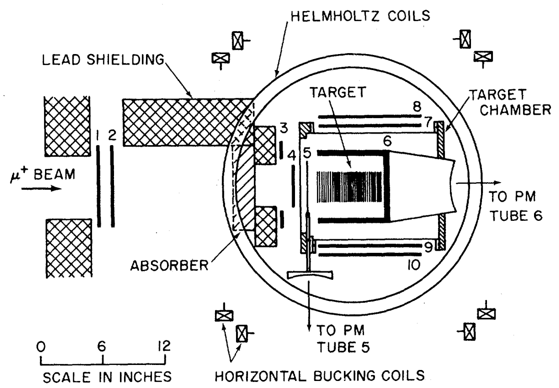


FIG. 1. Experimental arrangement for muonium measurements.

cidence with 7 8 or 9 10. A detailed description of the setup is given in a previous publication[5] (to be referred to hereafter as I). The experiment was carried out in three stages: the preliminary stage, muonium formation with thin gold foils in vacuum, and the background studies. The main features and the information extracted from the data taken during these experimental stages are discussed below.

II. PRELIMINARY MEASUREMENTS

In I we reported that the present experimental arrangement offered a sensitive method for the measurement of muonium formation in targets of small mass. For instance, at 2280 and 1290 Torr, the target thickness of argon gas confined in the effective target region described in I were 72 and 41 mg/cm^2, respectively; yet, based on the direct precession measurements, we found that the fraction R of stopped muons which form muonium were (85 ± 9) % and (64 ± 16) % at these corresponding gas pressures. Since the mass of the 200 thin gold foils was 3.3 g or 45 mg/cm^2, the effects on the rate of muonium production of introducing these foils into the target chamber containing argon gas of comparable effective mass should be significant. Therefore, in an exploratory experiment, we placed the foils inside the argon gas and made identical measurements on R as described in I. We found values of R equal to (98 ± 12)% and (85 ± 15)% for the foils in argon at 2280 and 1290 Torr, respectively. These observations led to the suggestion that the thin gold foil system when exposed to a stopping μ^+ beam provided a source for the formation of muonium.

To obtain R, the time spectra of the observed μ-e decay events were fitted by the single frequency distribution function[9]

$$N(t) = N_0 e^{-t/\tau}[1 + \tfrac{1}{2}R\alpha e^{-t/T}\cos(2\pi\nu t + \phi)] + B, \qquad (1)$$

where N_0 is the amplitude of decay events in the initial time channel, τ is the free-muon lifetime of 2.2 μsec, T is the muonium relaxation time, B is a constant associated with accidental events, ϕ is the phase of the signal, and ν is the precession frequency for the $(F, M_F) = (1, 1)$ state of muonium. The observed decay asymmetry is given by $\frac{1}{2}R\alpha$, in which α is a measure of the free-asymmetry coefficient anticipated under a condition in which the μ^+ remains free. Hence, R is the fraction of stopped muons which form muonium. An experimental value of $\alpha = 0.176 \pm 0.002$ was determined previously in a control experiment performed with graphite.[5] This result incorporated both the polarization of the positive muon beam emerging from the meson channel and corrections to the energy response and angular acceptance of the positron telescopes.

Best-fit values of the remaining parameters in the distribution function are listed in Table I. As is shown there, the muonium relaxation time T dropped sharply when the percentage of impurities in the argon gas and the relative importance of the dead layers in the target region increased due to a lowering of the gas pressure and/or the presence of the gold foils. This was understandable in terms of a shortening of the mean free path of muonium atoms in collision with the impurities. It should also be noted that a decrease in T will result in a larger value of R because of their intrinsic correlations appearing in Eq. (1). Consequently, the observation that R(foils in) > R(foils out) did not necessarily indicate a substantial enhancement of muonium signal caused by the introduction of foils, so further experiments of a direct search of muonium formation using gold foils in vacuum were required.

TABLE I. Muonium production in Ar and Au foils in Ar.

Parameters \ Target conditions	Ar	Ar and foils	Ar	Ar and foils
Pressure (Torr)	2280	2280	1290	1290
H (G)	−3.0	−3.0	−3.0	−3.0
Total events (in units of 10^3)	154	155	154	159
N_0	844 ± 2	822 ± 2	789 ± 3	837 ± 3
R	0.85 ± 0.09	0.98 ± 0.12	0.64 ± 0.16	0.85 ± 0.15
T (μsec)	2.8 ± 0.8	1.2 ± 0.3	0.7 ± 0.3	0.3 ± 0.1
ν (MHz)	4.19 ± 0.02	4.15 ± 0.03	4.12 ± 0.07	4.31 ± 0.11
ϕ	1.22 ± 0.12	1.39 ± 0.18	1.36 ± 0.15	1.50 ± 0.13
B	32	45	57	49
χ^2/Bin	1.05	1.04	1.18	1.05

III. THIN GOLD FOILS IN VACUUM

To establish more securely the observation of muonium formation by thin gold foils, we have carried out a series of measurements of R with two hundred 1000-Å-thick gold foils in vacuum at magnetic field values of $H = +8.4$, -10.5, -9.3, -7.0, and -5.0 G. The frequency ν of Larmor precession for muonium in states $|F, M_F\rangle = |1, 1\rangle$ or $|1, -1\rangle$ in a weak magnetic field H (in G) is approximately

$$\nu(\mathrm{MHz}) \simeq \mu_0^e H/h = 1.40H, \tag{2}$$

where μ_0^e is the electron-spin magnetic moment and h is Planck's constant. The time spectra of the μ-e decay events observed in the right- and left-arm telescopes (Fig. 1) were fit, respectively, to the distributions

$$N_R(t) = N_{0R}e^{-t/\tau}[1 + a\cos(2\pi\nu t + \phi)] + B_R \tag{3}$$

and

$$N_L(t) = N_{0L}e^{-t/\tau}[1 + a\cos(2\pi\nu t + \phi + \pi)] + B_L, \tag{4}$$

where $a \equiv \frac{1}{2}R\alpha e^{-t/T}$.

At thermal velocity ($\sim 6\times 10^5$ cm/sec), a muonium atom would require $\sim$200 nsec to travel across the vacuum space between two successive metal foils. Since collisions of muonium with metal surfaces may result in a depolarization of its spin, the muonium signal would be quenched, for the values of fields we used, in two or three precession cycles. The only significant data would appear in the early time channels (e.g., $t < 300$ nsec) of the observed time spectra. For purpose of analysis, therefore, we define the ratio

$$f(t) \equiv \frac{[N_R(t) - B_R] - [N_L(t) - B_L]}{[N_R(t) - B_R] + [N_L(t) - B_L]} = \frac{a\cos(2\pi\nu t + \phi) + (N_{0R} - N_{0L})/(N_{0R} + N_{0L})}{1 + [(N_{0R} - N_{0L})/(N_{0R} + N_{0L})][a\cos(2\pi\nu t + \phi)]} \simeq a\cos(2\pi\nu t + \phi) + b, \tag{5}$$

where ν is defined in (2) and a, b, and ϕ were considered as free parameters in this analysis.

Figure 2(a) shows the distribution function $f(t)$ observed for the run made with $H = -9.3$ G. When the data were fitted by (5), we obtained

$$a = 0.020 \pm 0.006. \tag{6}$$

The solid curve shows the best fit. The error bars shown represent one standard deviation (statistical only). As a calibration, we have also measured the muonium formation probability in a thin target (178 mg/cm^2) of quartz at $H = -10.0$ G. Applying the same analysis to the quartz data, we obtained

$$a = 0.022 \pm 0.004. \tag{7}$$

The best fit and the reduced data points of quartz are shown in Figure 2(b) for comparison.

Table II lists the values of the parameter a obtained using (5) for those runs which are applicable; i.e., those data which were taken with both right- and left-arm positron telescopes simultaneously employed.

The weighted mean of the parameter a obtained for all gold-foil runs in a vacuum environment was $a = 0.0135 \pm 0.0030$. Using the quartz run as a standard reference, we found that the probability of muonium formation with thin gold foils in vacuum was

$$R = 0.28 \pm 0.06. \tag{8}$$

Since the above analysis averaged out the effects of spin relaxation T on R, we have also carried out a frequency analysis[10] based on Eqs. (3) and (4). In this frequency analysis we computed the best-

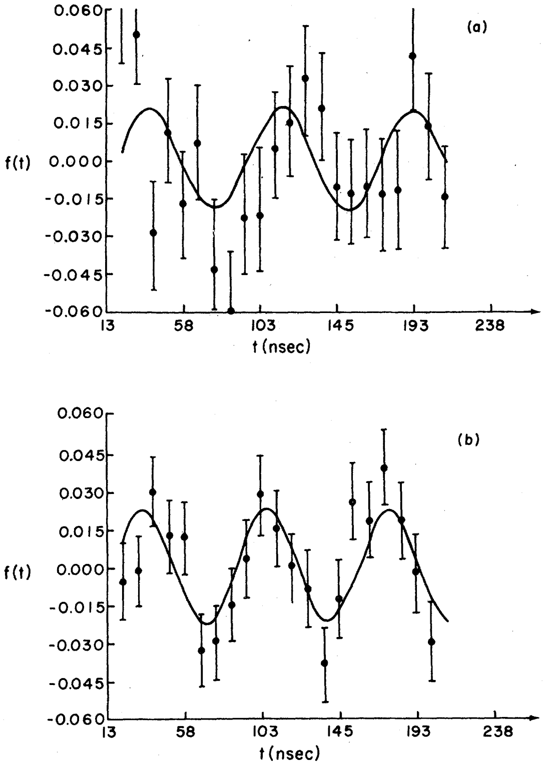


FIG. 2. Comparison of the reduced data with $f(t) = a\cos(2\pi\nu t + \phi) + b$ for the runs (a) 200 foils in vacuum at $H = -9.3$ G and (b) $\frac{1}{32}$-in. quartz target at $H = -10$ G. The reduced data represent the ratio $[(N_R^i - B_R) - (N_L^i - B_L)]/[(N_R^i - B_R) + (N_L^i - B_L)]$, where N^i represents the number of events observed in the ith time interval. The error bars indicate the statistical errors only.

TABLE II. Running conditions and best-fit values of the parameters R and a. The values of R listed here are obtained from a Fourier-frequency analysis of the data. A blank indicates that only one decay positron arm was used and hence an analysis for the parameter a was not possible [see text and Eq. (5)].

Run No.	Target	H (G)	Total events (in units of 10^3)	R	a
A	200 Au foils	+8.4	1760	0.24± 0.09	0.011± 0.005
B	200 Au foils	−10.5	715	0.32± 0.15	0.020± 0.006
C	200 Au foils	−9.3	790	0.45± 0.10	0.020± 0.006
D	200 Au foils	−7.0	288	0.41± 0.12	···
E	200 Au foils	−5.0	1639	−0.06± 0.10	0.003± 0.006
F	Frame only	−3.0	250	0.07± 0.12	···
G	Frame only	−9.0	952	0.10± 0.12	0.001± 0.001
H	800 Au foils	−5.0	2351	−0.01± 0.06	0.001± 0.003
I	800 Au foils	+21.0	1083	−0.04± 0.13	0.000± 0.005
J	$\frac{1}{32}$-in. quartz	−10.0	1265	0.45± 0.06	0.022± 0.004

fit value of R by a maximum likelihood method for a continuous assignment of ν, with all other parameters in Eqs. (3) and (4) fixed. To be precise, we we have determined the values of N_0 and B from the best fits of the data to the distribution function $N_0 e^{-t/\tau} + B$, and then determined the relaxation parameter T by performing a χ^2 mapping versus the two adjustable parameters R and T, with the phase angle ϕ and the asymmetry parameter α fixed at 1.85 ± 0.01 and 0.176 ± 0.002 rad, respectively, corresponding to the values determined in the graphite and quartz runs.[5] Such a χ^2 mapping yielded $T = (200^{+200}_{-100})$ nsec for the data taken with 200 gold foils in vacuum. Relaxation times in this range are consistent with the proposed mechanism wherein thermal muonium precesses as it travels between the successive foils. Once the values of N_0, B, ϕ, α, and T were determined, the frequency analysis followed. The results are shown in Fig. 3 with best-fit values of R plotted against ν/H. The dotted points are the best-fit values of R obtained from the maximum likelihood fit; the error bars represent one standard deviation error. Each solid curve is a theoretical calculation of the Fourier transform of the oscillating distribution function

$$\Delta N(t) = C_0 e^{-t/\tau} e^{-t/T} \cos(2\pi\nu t + \phi),$$

in which C_0 is a normalization constant. The central maximum of each curve was chosen at the muonium precession frequency ν corresponding to the measured field H, as predicted from Eq. (2). The theoretical curves were normalized so that the peak amplitudes of the curves equaled the peak values obtained in the data analysis. The full width at half-maximum resulting from the χ^2 analysis correlated well with the muonium relaxation time T. The good agreement between the data points and the solid curves indicates strong evidence for muonium formation with gold foils in vacuum.

The null result obtained for $H = -5$ G could be explained on the assumption that at thermal velocities the muonium atoms would survive for only one cycle at this field before traversing the distance of

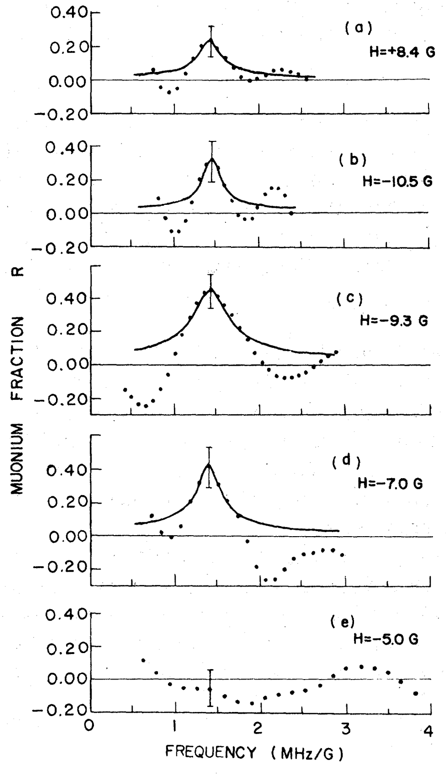


FIG. 3. Results of frequency analyses on data for the 200 gold foil runs in vacuum. The best-fit values of R are plotted against ν/H. Hence the muonium signal, if any, would be expected at 1.4 MHz/G.

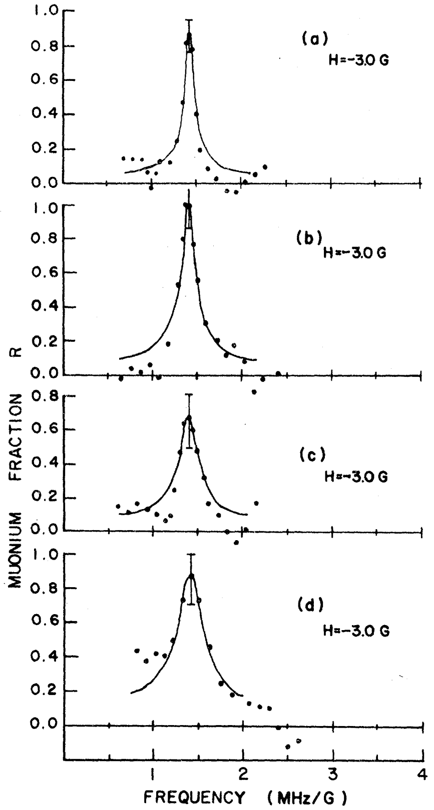


FIG. 4. Results of frequency analyses on data for muonium precession in argon gas at 2280 Torr for (a) foils out, (b) foils in, and at 1290 Torr for (c) foils out, (d) foils in.

0.08 cm between the foils, a period which may represent too stringent a requirement on the analysis. Values of R resulting from the frequency analyses are summarized in Table II. The weighted mean of R for all runs of Au foils in vacuum including the $H=-5$ G run, was

$$R=0.28\pm0.05. \tag{9}$$

This result agrees with that of Eq. (8), for which the effect of spin relaxation was averaged out. Since positive muons stopping in the dead layers of the veto scintillation counters can contribute only to background, the value for R quoted in Eq. (9) represents a lower limit.

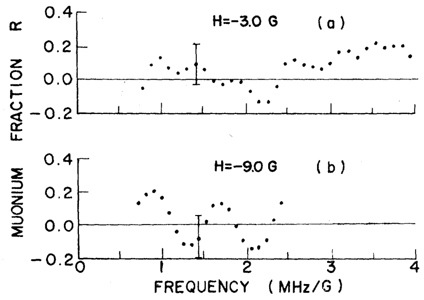
A frequency analysis has also been applied to the data obtained from the exploratory experiments. The results are presented in Fig. 4. The agreement between the results obtained from the frequency analysis and that from a straightforward multiparameter fit utilizing Eq. (1) as described in Sec. II is excellent.

IV. STUDY OF SOURCES OF BACKGROUND

In an attempt to isolate unambiguously the source for our apparent muonium signal, we carried out a series of "background" studies. In particular, we looked for contributions to a muonium signal (i) originating in the supporting frame holding the gold foils and (ii) from muonium atoms which themselves adhere to the surface of the foils.

To ascertain whether there was a contribution to the muonium signal due to muons stopping in the background material of the supporting frame, we repeated the measurements of R with the foils removed. As shown in Figs. 5(a) and 5(b), we found no evidence of muonium formation in the supporting frame. Hence, we attributed the entire muonium signal to the gold foils themselves.

To determine whether the muonium precession signals described in Sec. III resulted from free-muonium atoms located in the vacuum region between the foils or partly from those atoms chemically bound to the surface of foils, we carried out a direct measurement on R with 800 gold foils in vacuum. The 800 foils were packed in the same volume used for 200 foils. The average mean free path of muonium at most was ~0.02 cm and there-



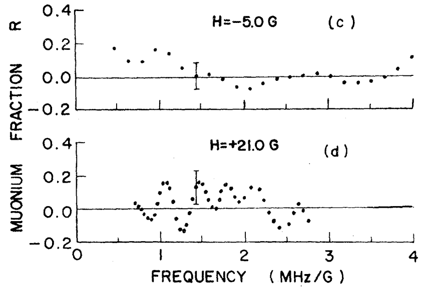


FIG. 5. Results of frequency analyses on data for runs with foils removed at (a) $H=-3.0$ G, (b) $H=-9.0$ G, and with 800 foils in vacuum at (c) $H=-5$ G and (d) $H=+21.0$ G.

fore, free thermal muonium atoms would be destroyed within ~ 50 nsec of production by collisions with gold foils. However, if the muonium atoms produced in the target were adsorbed to the surface of the foils and could precess as stable muonium, a relatively large muonium signal in these runs having 800 foils would be expected. As shown in Figs. 5(c) and 5(d), we found no evidence for muonium formation in runs with 800 foils in vacuum. Instead, the data for this target were consistent with the free muon precession found in the control experiment using graphite.

In conclusion, we believe that the presence of thermal muonium atoms in the vacuum region between thin gold foils has been demonstrated. The lower limit of the probability of muonium formation by such an array of thin foils is $R = 0.28 \pm 0.05$.

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